Chapter 7
Laboratory Investigations

7-1. Purpose

The purpose of laboratory tests is to investigate the physical and hydrological properties of natural materials such as soil and rock, determine index values for identification and correlation by means of classification tests, and define the engineering properties in parameters usable for design of foundations. The engineering geologist and/or geotechnical engineer, using the test data and calling upon experience, can then accomplish safe and economical designs for engineering structures. Procedures to assure quality in laboratory testing are outlined in ER 1110-1-261 and -8100. This chapter is divided into four sections that discuss selection of testing methods and samples, index and classification tests, engineering properties of soil, engineering properties of rock, and engineering properties of shales and moisture-sensitive rocks. No attempt has been made to describe the techniques for performing individual tests; references are provided for that purpose. A wide range of soil and rock tests are identified, and the appropriate applications are discussed.

Section I
Test and Sample Selection

7-2. Needs for Test and Sample Selection

The selection of samples and the number and type of tests are largely influenced by local subsurface conditions and the size and type of structure. Table 7-1 lists references that provide guidance for assigning laboratory tests for various types of structures. As a minimum, all soil samples should be classified according to the USCS (paragraph 5-8), and moisture contents should be determined on cohesive soils and on unsaturated granular soils that have 12 percent or more fines. Rock cores should be visually classified and logged prior to laboratory testing. The geologic model (paragraph 3-1) can be further developed using the results of basic indexing of soils and rock cores, together with other geotechnical data obtained from field reconnaissance and preliminary investigations. The geologic model, in the form of profiles and sections, can be used to indicate where additional indexing of soils and rock is needed, as well as the type and number of tests required to determine the engineering properties of all materials influencing the project. As more data become available, the testing requirements should be reviewed and modified as necessary.

a. Selection of samples for testing. Most index testing of soil and rock is performed on disturbed samples, i.e., samples that have not had special handling to preserve structural integrity. However, to determine natural water content the sample must be protected from drying. For soils, protection can be accomplished by using sealed metal tubes or plastic or glass jars. For rock, samples are normally waxed to prevent drying. Because many laboratory tests, particularly those to determine engineering properties, require "undisturbed" samples, great care must be exercised in storing, selecting, shipping, and preparing these materials. The geologist and/or geotechnical engineer responsible for applying test data to project requirements should have positive control of sampling and shipping of soil and rock samples. Table 7-2 lists some of the factors that may cause undisturbed samples to be less representative of the conditions encountered on the project.

b. Distribution and size of samples. The distribution of locations of soil and rock tests should be evaluated periodically. Within the project requirements, a suitable suite of index and engineering

Table 7-1
Guidance for Assigning Laboratory Tests

Type of Structure or Work	Reference
Embankment dams	EM 1110-2-2300 EM 1110-2-1902
Concrete gravity dams	EM 1110-2-2300 EM 1110-2-1902
Buildings and other structures	TM 5-818-1
Deep excavations	TM 5-818-5/AFM 88-5, Chapter 6/NAVFAC P-418
Tunnels and shafts in rocks	EM 1110-2-2901
Breakwaters	EM 1110-2-2904
Pile structures and foundations	EM 1110-2-2906
Levees	EM 1110-2-1913

Table 7-2
Factors Causing Undisturbed Samples to be Less Representative of Subsurface Materials

	Effect on	
Factor	**Soils**	**Rocks**
Physical disturbance from sampling and transportation	Effect on shear strength: a. Reduces Q and UC strength. b. Increases R strength. c. Little effect on S strength. d. Decreases cyclic shear resistance. Effect on consolidation test results: a. Reduces P b. Reduces C^{c} c. Reduces c_v in vicinity of σ_p and at lower stresses. d. Reduces C_{α}.	Cause breaks in core; may be difficult to obtain intact specimens suitable for testing May seriously affect weakly cemented materials, e.g., for sandstones, may destroy evidence of significant cementation. Foundation may appear to be more fractured than it is May prevent testing of some materials May reduce deformation modulus, E
Changed stress conditions from in situ to ground surface locations	Similar to physical disturbance but less severe	Stress relief may cause physical disturbance similar to that from sampling and transportation. Deformation modulus reduces with decreasing stress field
Contamination of sands from drilling mud	Greatly reduces permeability of undisturbed samples	

Note: Q = Unconsolidated-undrained triaxial test; UC = Unconfined compression test; σ_p = Preconsolidation pressure; C_c = Compression index; c_v = Coefficient of consolidation; = C_{α}= Coefficient of secondary compression; R = Consolidation-undrained triaxial test; S = Drained direct shear test.

property tests should be planned both in the vertical as well as lateral direction. Duplication of costly, complex tests should be avoided except where statistical balance is required. If it becomes apparent in the application of the test data that coverage of field conditions is irregular, or missing in certain stratigraphic units, field sampling procedures should be revised. Undisturbed sample sizes for soils should conform to those given in Appendix F. Rock sample sizes can range from 4.763 to 20 cm (1.875 to 6.0 in.). Large-diameter cores are obtained in lieu of the smaller core sizes in cases where rock defects make core recovery and sample quality difficult to attain. In some cases, the test procedure may dictate sample size. Rock tests and procedures are presented in the Rock Testing Handbook (USAEWES 1993).

Section II
Index and Classification Tests

7-3. Soils

Types of index and classification tests that are typically required are listed in Table 7-3 together with their reporting requirements. Initially, disturbed samples of soils are classified according to the USCS. Upon visual verification of the samples, Atterberg limits, mechanical analyses, and moisture content tests will be performed (Schroeder 1984: Gillott 1987). Table 7-3 also presents two other index tests relating to durability under cyclic weather conditions (slaking tests), and shear strength (torvane and penetrometer). The torvane and penetrometer shear tests are simple and relatively inexpensive; however, the test results can be widely variable and should be used with caution. These shear tests can be helpful as a guide to more comprehensive tests. Slaking tests are valuable if the project is located in moisture sensitive clays and clay shales, and foundation design requirements indicate that the foundation and cut slope areas will be exposed temporarily to wetting and drying conditions.

Table 7-3
Index and Classification Tests for Soils

Test	Remarks
Water content[1]	Required for every sample except clean sands and gravels
Liquid limit and plastic limit[1]	Required for every stratum of cohesive material; always have associated natural water content of material tested (compute liquidity index) [2]
Sieve	Generally performed on silts, sands, and gravels (> 200 mesh)
Hydrometer analysis	Generally performed on soils finer than the No. 10 sieve size (medium sand and finer). Correlate with Atterberg limit tests to determine the plasticity of the soil
Slaking test	Performed on highly preconsolidated clays and clay shales where deep excavations are to be made or foundations will be near-surface. Wet and dry cycles should be used
Pocket penetrometer and torvane	Performed on cohesive materials, undisturbed samples, and intact chunks or disturbed samples. Regard results with caution; use mainly for consistency classification and as guide for assigning shear tests
X-ray diffraction	Generally performed on clays and clay shales to determine clay mineralogy which is a principal indicator of soil properties

[1] See EM 1110-2-1906 for procedures.
[2] Liquidity index = $LI = \frac{w_n - PL}{LL - PL}$. ($w_n$=natural water content).

7-4. Rock

All rock cores will be logged in the field and the log verified by the project geologist or geotechnical engineer prior to selection of samples for index and classification tests. Types of index and classification tests which are frequently used for rock are listed in Table 7-4. Water content, unit weight, total porosity, and unconfined (uniaxial) compression tests will be performed on representative cores from each major lithological unit to characterize the range of properties. The RQD values (TM 5-818-1), as developed by Deere (1964), may be assigned to rock cores as a guide prior to testing. Additional tests for bulk specific gravity, apparent specific gravity, absorption, elastic constants, pulse velocity, and permeability, as well as a petrographic examination, may be dictated by the nature of the samples or by the project requirements (Das 1994). Samples of riprap and aggregate materials will be tested for durability and resistance to abrasion, and the specific gravity of the solids should be determined. Data from laboratory index tests and core quality conditions may be used for rock classification systems such as those developed by Bieniawski (1979) and Barton, Lien, and Lunde (1974).

Table 7-4
Laboratory Classification and Index Tests for Rock

Test	Test Method	Remarks
Unconfined (uniaxial) compression	RTH 111[1]	Primary index test for strength and deformability of intact rock
Specific gravity of solids	RTH 108[1]	Indirect indication of soundness of rock intended for use as riprap and drainage aggregate
Water content	RTH 106[1]	Indirect indication of porosity of rock or clay content of sedimentary rock
Pulse velocities and elastic constants	RTH 110[1]	Index of compressional wave velocity and ultrasonic elastic constants for correlation with in situ geophysical test results
Rebound number	RTH 105[1]	Index of relative hardness of intact rock cores
Permeability	RTH 114[1]	Intact rock (no joints or major defects)
Petrographic examination	RTH 102[1]	Performed on representative cores of each significant lithologic unit
Specific gravity and absorption	RTH 107[1]	Indirect indication of soundness and deformability
Unit weight and total porosity	RTH 109[1]	Indirect indication of weathering and soundness
Durability	TM 5-818-1, Federal Highway Administration (1978) Morgenstern and Eigenbrod (1974)	Index of weatherability of rock exposed in excavations and durability of rock for rockfill and riprap
Resistance to abrasion	RTH 115[1]	Los Angeles abrasion test; limited usefulness for evaluating weatherability of riprap
Point load testing	RTH 325[1]	May be used to predict other strength parameters with which it is correlated

[1] Rock Testing Handbook (USAEWES 1993).

Section III
Engineering Property Tests - Soils

7-5. Background

Reference should be made to EM 1110-2-1906 for current soil testing procedures and EM 1110-1-1904 for methods of settlement analysis.

a. Shear strength. Shear strength values are generally based on laboratory tests performed under three conditions of test specimen drainage. Tests corresponding to these drainage conditions are: unconsolidated-undrained Q tests in which the water content is kept constant during the test; consolidated-undrained R tests in which consolidation or swelling is allowed under initial stress conditions, but the water content is kept constant during application of shearing stresses; and consolidated-drained S tests in which full consolidation or swelling is permitted under the initial stress conditions and also for each increment of loading during shear. The appropriate Q, R, and S tests should be selected to reflect the various prototype loading cases and drainage conditions. Normally, strength tests will be made with the triaxial compression apparatus except S tests on fine-grained (relatively impervious) soils, which generally are tested with the direct shear apparatus because of time constraints using the triaxial apparatus. Where impervious soils contain significant quantities of gravel sizes, S tests should be performed on triaxial compression apparatus using large-diameter specimens.

(1) Q test. The shear strength resulting from a Q test corresponds to a constant water content condition, which means that a water content change is not permitted prior to or during shear. The Q test conditions approximate the shear strength for short-term conditions, e.g., the end-of-construction case. In cases where a foundation soil exists that is unsaturated but will become saturated during construction, it is advisable to saturate undisturbed specimens prior to axial loading in the Q test.

(2) R test. The shear strength resulting from an R test is obtained by inducing complete saturation in specimens using backpressure methods, consolidating these specimens under confining stresses that bracket estimated field conditions, and then shearing the specimens at constant water content. The R test applies to conditions in which impervious or semipervious soils that have been fully consolidated under one set of stresses are subject to a stress change without time for consolidation to take place.

(3) S test. The shear strength resulting from an S test is obtained by consolidating a sample under an initial confining stress and applying shear stresses slowly enough to permit excess pore water pressures to dissipate under each loading increment. Results of S tests are applicable to free-draining soils in which pore pressures do not develop. In cohesive soils, S tests are used for evaluating the shear strength of long-term conditions, e.g.,"normal operating" case. The R-bar test, a consolidated, undrained triaxial test in which pore pressures are measured during shear to determine the effective stress, has sometimes been used by a USACE district in lieu of the S test.

(4) Selection of design shear strengths. When selecting design shear strengths, the shape of the stress-strain curves for individual soil tests should be considered. Where undisturbed foundation soils and compacted soils do not show a significant drop in shear or deviator stress after peak stresses are reached, the design shear strength can be chosen as the peak shear stress in S direct shear tests, the peak deviator stress, or the deviator stress at 15 percent strain where the shear resistance increases with strain. For each soil layer, design shear strengths should be selected such that two-thirds of the test values exceed the assigned design values.

b. Permeability. To evaluate seepage conditions, reasonable estimates of permeability of pervious soils are required. Field pumping tests (TM 5-818-5) or correlations between a grain-sized parameter (such as D_{10}) and the coefficient of permeability, as in Figure 3-5, EM 1110-2-1913, are generally used for coarse-grained materials below the water table. The permeability of compacted cohesive soils for embankments and backfills and for soils modified in place is generally estimated from consolidation tests. Laboratory permeability tests are also being used more frequently for these materials.

c. Consolidation and swell. The parameters required to perform settlement and rebound analyses are obtained from consolidation tests on highly compressible clays or on compressible soils subjected to high stresses. Swell tests are also performed to identify, confirm, and quantify swelling ground conditions in tunneling. The sequence and magnitude of test loading should approximate the various prototype loading cases for which settlement and rebound analysis are to be performed. For expansive soils, the standard consolidation test or a modification of the test (Johnson, Sherman, and Al-Hussaini 1979) may be used to estimate both swell and settlement. Consolidometer swell tests tend to predict minimal levels of heave. Soil suction tests (Johnson, Sherman, and Al-Hussaini 1979) can be used to estimate swell. However, this test tends to overestimate heave compared with field observations. Gillott (1987) describes various tests to evaluate expansive soils.

Section IV
Engineering Property Tests - Rock

7-6. Background

Table 7-5 lists the laboratory tests frequently performed to determine the engineering properties of rock. These and other rock tests are presented in the Rock Testing Handbook (USAEWES 1993) and Nicholson (1983b).

Table 7-5
Laboratory Tests for Engineering Properties of Rock

Test	Reference	Remarks
Elastic moduli from uniaxial compression test	RTH 201[1]	Intact rock cores
Triaxial compressive strength	RTH 202[1]	Deformation and shear strength of core containing inclined joints
Direct shear strength	RTH 203[1]	Strength along planes of weakness (joints) or rock-concrete contact
Creep in compression	RTH 205[1]	Intact rock from foundation where time-dependent compression is an important factor in design
Thermal diffusivity	RTH 207[1]	Intact rock subjected to elevated temperatures such as adjacent to mass concrete where heat conductance is a factor

[1] Rock Testing Handbook (USAEWES 1993).

a. Unconfined uniaxial compression test. The unconfined uniaxial compression test is performed primarily to obtain the elastic modulus and unconfined compressive strength of a rock sample. Poisson's ratio can be determined if longitudinal and lateral strain measurements are made on the sample during the test. The value of Poisson's ratio is required for describing the deformation characteristics of a rock mass. Occasionally, design requirements dictate the need for testing of samples at different orientations to describe 3-D anisotropy. This test is economical, adequate for most foundation testing, and therefore a useful test for smaller projects. See USAEWES (1993), methods RTH 201-89 (ASTM D 3148-86 (ASTM 1996g)) and RTH 205-93 (ASTM D 4405-84 (ASTM 1996i)) for standard test methods.

b. Point load tests. Although the point load test is, strictly speaking, an index test for rock, it can be equated with the unconfined uniaxial compression strength. Its advantage lies in the ease with which the test can be conducted. The testing apparatus is portable so that it can be used in the field to test cores as they are retrieved from the ground. In this way, a statistically significant amount of data can be collected economically and with minimal effects from aging and handling of the cores. In addition, the tests can be run both perpendicular and parallel to the axis on the same piece of core, cut block, or irregular lump to provide a measure of the anisotropy of the rock strength. RTH 325-89 (USAEWES 1993) presents the suggested method for conducting point load strength tests.

c. Tensile strength. The tensile strength of rock is normally determined by the Brazilian method (RTH 113-93 (USAEWES 1993)) in which a piece of core is split along its axis. In some cases, direct pull tensile tests are conducted, but these samples are much harder to prepare. Results of the tensile strength tests provide input that can be used in the design of underground openings.

d. Unit weight. Determination of the unit weight of the various lithologies at a site is an important piece of engineering data. It is used for input into blast performance and muck handling, among other things. Since the unit weight is a nondestructive test, the sample can be subjected to additional tests after the unit weight is determined.

e. Direct shear test. Laboratory triaxial and direct shear tests on intact rock cores and intact rock cores containing recognizable thin, weak planes are performed to determine approximate values of cohesion, c (shear strength intercept) and φ (angle of internal friction) of a rock type. Detailed procedures for making the laboratory direct shear test are presented in RTH 203-80 (USAEWES 1993). The test is performed on core samples ranging from 6.5 to 20 cm (2 to 6 in.) in diameter. The samples are trimmed to fit into a shear box or machine and oriented so that the normally applied force is perpendicular to the feature being tested. Results of tests on intact samples will give upper-bound strength values while tests on smooth surfaces give lower-bound values. Repetition of the shearing process on a sample, or continuing, displacement to a point where shear strength becomes constant can ultimately establish the residual shear strength value. Where natural discontinuities control the rock mass shear strength, tests should be performed to determine the friction angle of the discontinuity asperities as well as the smooth discontinuity plane. The direct shear test is not suited to the development of exact stress-strain relationships because of the nonuniform distribution of shearing stresses and displacements within the test specimen. The bonding strength of a rock/concrete contact can be determined by this test. Values of cohesion and angles of internal friction are used to determine strength parameters of foundation rock. These values are the principal parameters in the analytical procedures to define the factor of safety for sliding stability and for some bearing capacity analysis. They are appropriate in analyses of the stability of rock slopes and of structures subjected to nonvertical external loading. For the test results to have valid application, test conditions must be as close as possible to actual field conditions. This includes selection of the normal loads to be used. Since the failure envelope is nonlinear at the lower load ranges, testing performed with too little or too much normal load will not adequately model actual conditions and will yield inappropriate values of c and φ. The application of these values is discussed in detail in Corps of Engineers guidance on gravity dam design (EM 1110-1-2908), and in Ziegler (1972) and Nicholson (1983a).

f. Triaxial shear test. The triaxial shear test can be made on intact, cylindrical rock samples. The test provides the data for determination of rock strength in an undrained state under 3-D loading. Data from the test can provide, by calculation, the strength and elastic properties of the rock samples at various confining pressures, the angle of internal friction (shearing resistance), the cohesion intercept, and the deformation modulus. Strength values are in terms of total stress as pore water pressure is not measured, and corrections should be made accordingly. The standard test method is presented as RTH 202-89 (USAEWES 1993) (ASTM D 2664-86 (ASTM 1996f)). A variation of this test using multistage triaxial loading (RTH 204-80 (USAEWES 1993)) is sometimes used to evaluate the strength of joints, seams, and bedding planes at various confining pressures.

g. Other testing. There are numerous other engineering properties (e.g., toughness, abrasiveness) of rock that are of interest in different applications and all have different testing procedures. The designer is advised to search the literature, including the RTH, to determine which testing is appropriate.

Section V
Engineering Property Tests - Shales and Moisture-Sensitive Rocks

7-7. Index Testing

Most moisture-sensitive geomaterials are sedimentary or metamorphic in origin. These include clays, clay shales, poorly to moderately cemented sandstones, marl, and anhydrite. Most commonly, moisture-sensitive rock and sediment contain clay minerals, particularly smectites, which have the capacity to hold large volumes of interstitial water. In some cases, the weathered product of a rock type may be the sensitive material in the overall rock mass and can be the result of chemical weathering (saprolite) or rock movement (fault gouge, mylonite). As these rock forms have soil-like characteristics, the index properties (Atterberg limits, moisture content, etc.) of these materials should be determined prior to more comprehensive testing. The results of the index testing usually indicate the engineering sensitivity of the rock forms and should be used as a guide to further testing. Special procedures that may be necessary for index testing can be found in EM 1110-2-1906.

a. Direct and triaxial shear tests. Most direct and triaxial shear tests conducted on hard, brittle rock samples are of the undrained type. For these particular types of materials, pore pressures do not play a dominant role, and strength values are in terms of total stress. However, as softer rock types are encountered, with correspondingly higher absorption values (e.g., greater than 5 percent), the role of pore pressure buildup during the rock shearing process becomes more important. The same condition is true for many clay shales and other similar weak and weathered rock materials. For moisture-sensitive rocks, soil property test procedures should be used if possible. Critical pore pressures that may substantially reduce the net rock strength can then be monitored throughout the entire testing cycle. Where hydraulic concrete structures are to be constructed on clay shales or shales, shear testing should be conducted to determine the strength of the shale/concrete interface.

b. Test data interpretation. Laboratory test data on shales and moisture-sensitive rocks should be interpreted with caution. The laboratory undrained strength of intact specimens is rarely representative of in-place field shear strengths. Frequently, shales, clay shales, and highly overconsolidated clays are reduced to their residual shear strength with minor displacements. The geotechnical explorations, laboratory testing, and review of field experiences must establish whether residual or higher shear strengths are appropriate for design purposes. Results of laboratory tests should be confirmed by analysis of the field behavior of the material from prior construction experience in the area, analysis of existing slopes or structures, and correlation with similar geologic formations at sites where the field performance is known. For a general engineering evaluation of the behavioral characteristics of shales, see Table 3-7, TM 5-818-1, Underwood (1967), and Townsend and Gilbert (1974); for physical properties of various shale formations, see Table 3-8, TM 5-818-1. Slope stability of shales can be analyzed using the PC-based, menu-driven program, UTEXAS3 (Edris 1993), ROCKPACK (Watts 1996) or the International Forum on Discontinuous Deformation Analysis Method (International Forum on Discontinuous Deformation Analysis and Simulations or Discontinuing Media 1996).

7-8. Swelling Properties

For many shales and moisture-sensitive rocks, swelling characteristics are a key consideration. Where used as fill, their physical properties can change significantly over time, and in response to the presence of water (Nelson and Miller 1992). In addition, swelling of in situ rock has caused heave in foundations, slope failures, distress in slope treatments such as shotcrete, and failure of tunnel linings (Olivier 1979). EM 1110-1-2908 has a thorough discussion of the testing procedures used to evaluate swelling potential of rock and soil. For the constant volume test, great care should be exercised in interpreting the results. The procedure currently in use calls for increasing applied load periodically during the test to return the specimen to its original dimensions. This load may exceed the actual swell pressure because it also must to overcome the elastic properties of the rock.